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HEAT TRANSFER TO A GAS CONTAINING A CLOUD OF PARTICLES

Andrew McAlister, Henderson C. Ward, and Clyde Orr, Jr.

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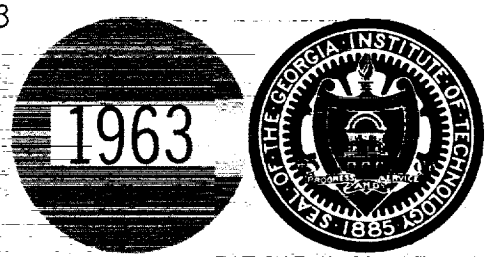

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I. SUMMARY

The objective of this project is to provide basic information on radiant heat transfer to gas-particle systems. The results are intended to aid the analysis and engineering application of high temperature heat transfer processes. The project is concerned with evaluating the absorptive power of suspended particles and describing quantitatively the conductive dissipation of heat from the particles to the surrounding gas.

Particle absorptivity and emissivity data are quite limited. Further, theoretical evaluation of these properties is a lengthy process, and, at best, results of partial applicability only can be obtained. For present uses, therefore, theoretical calculations are to be used as a guide to determine empirical formulations, much as is done in other areas of heat transfer. Emphasis is to be placed on the collection of experimental data, taking into account changes in pertinent variables. A general correlation will then be attempted in terms of such characteristic ratios as particle size to penetration thickness, particle size to wave length, and penetration thickness to wave length.

Analysis of unsteady state heat transfer between spherical particles suspended in a nonabsorbing gas and subjected to a constant radiant heat flux has been continued. Numerical calculations have been carried out for selected values of material properties and particle dimensions partially covering the ranges to be investigated experimentally. The results, summarized in graphical form, give the particle temperatures and surrounding gas temperatures at arbitrarily selected distances from the particle surfaces as functions of the gas and particle physical properties and the particle concentration. The numerical calculations are intended to show which effects are important and which may be neglected. They have the further objective of

establishing a more realistic analysis that will incorporate nonuniformity of particle concentration, velocity distribution, temperature distribution, radiant energy flux and turbulent mixing effects.

An apparatus with which to investigate experimentally both the absorptive properties of particles and the particle-gas heat transfer interaction is almost completed. With it an aerosol well characterized as to particle shape, size, surface area, and concentration will be exposed to a radiant field in which convection and conduction heat effects are reduced to a minimum. The radiant energy absorbed and, if possible, the particle and gas temperatures will be measured calorimetrically. The apparatus consists basically of a particle cloud generation system, a closed system for aerosol circulation, a powder recovery system, a furnace for generating a radiant field, and a calorimeter for measuring the heat absorbed by the aerosol from the radiant field. A quartz tube is employed to conduct the aerosol through the radiant field and to allow exposure to the radiation there. Approximately 75 per cent of the radiant flux generated by the furnace at 2300° F will penetrate the quartz. Auxiliary equipment for the system includes a device for monitoring particle concentrations, a thermocouple network for temperature determination, and power controls for operating the furnace. It is estimated that particle clouds up to 0.05 per cent by volume or, perhaps, 75 per cent by weight, and flowing up to 50 ft/sec can be studied. The calorimeter is capable of measuring heats of absorption as low as 10 Btu/hr with acceptable accuracy.

The system is complete except for the particle concentration monitoring system. Experimental work for the immediate future must be devoted to calibrating the various measurement systems of the apparatus. Subsequently,

collection of experimental data can begin. It is anticipated that sufficient data will be collected in the near future for a significant evaluation of particulate radiation properties and for guiding the study of the overall heat transfer process. Thereafter, measurements of the particle and gas temperatures will be initiated.

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II. INTRODUCTION

Clouds of particles suspended in an essentially transparent gas increase the absorptive properties of the system and provide radiation shielding when interpositioned between high temperature radiation sources and objects. Engineering data, however, are needed for making practical use of these properties. The objective of this project is to analyze theoretically and experimentally the radiant heat transfer to a solid-gas suspension in order to provide information that can be used in guiding engineering work with such systems.

Theoretical analyses are included that assess the absorptive properties of small particles and evaluate the rate of radiant heat transfer and the temperature distributions resulting from the conduction of energy from absorbing particles to a surrounding gas. An experimental apparatus is described with which it is to be possible to measure the absorptive power of selected, explicitly defined, particle clouds and to determine the temperature of the solid and gas phases as they emerge from exposure to a radiant field.

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III. THEORETICAL ANALYSIS

A. Absorptivity and Emissivity

Basic to any evaluation of the effectiveness of a particle cloud as an absorber of radiant energy and then as a source of heat for the surrounding gas is the absorptive characteristics of the individual particles. Absorptivity and emissivity data for particle materials are quite limited in the literature and values cannot be reliably estimated from the radiation properties of large plane surfaces. Previous considerations[1,2,3] of radiation to clouds of particles have primarily been made in connection with furnace calculations, and here, because of many other difficulties, it has been found expedient to assume that the particles are black. In actuality, however, particles smaller than 100 microns in diameter may be far from black body absorbers. Even graphite, for instance, is not a black body when dispersed as a fine particle cloud. The nearness of particle dimensions to the penetration thickness, i.e., the material thickness required to reduce the amplitude of an impinging wave to 1/e of its original value, and to the wave length of the incoming radiation can have extensive effects. For metals this thickness will be on the order of one micron while for nonconductors it can be as high as one tenth of an inch.[4] In addition to particle size, the surface condition of the suspended particles is a highly significant parameter if measurements on large plane surfaces are any guide.

For a given particle-gas system the radiation properties are practically impossible to evaluate by theoretical means. Although the Mie theory[5] describes electromagnetic absorption processes exactly, solutions to its equations require lengthy operations, especially as the particle radius

increases. The presence of an absorbing media having a complex refractive index makes the task even more formidable. The many texts and reports[5,6,7] on the subject serve as examples of the tremendous efforts required to produce really very limited results. The theoretical computations that have been made, therefore, amount to approximations of the rigorous Mie formulae and are limited to specific cases of radiation wave length, particle shape, particle size and refractive index. In general, even calculations for highly idealized conditions involve series functions with a large number of terms for acceptable convergence.

This being the case, the only practical approach for evaluating particle radiation properties is to use the rigorous calculations as guides to determine empirical formulations, much as is done with dimensionless quantities in other areas of heat transfer. Experimental data can then be sought to relate particle radiation absorptivities and emissivities to particle size, minimum absorption thickness, particle surface area and radiation wave length, since these variables have definite and characteristic influences on particle radiation properties. Further, experimental domains can be extended to uninvestigated situations by analyzing the data in terms of such characteristic ratios as those of particle size to absorption thickness, particle size to wave length, and absorption thickness to wave length.

In view of the above, this investigation is being concentrated on the experimental determination of particle behavior rather than on theoretical evaluations. It is believed that this approach will yield results more applicable to present problems than a theoretical development which would still need experimental verification.

B. Unsteady Heat Transfer

The differential equation and the initial and boundary conditions describing the unsteady heat transfer between spherical particles suspended in a nonabsorbing gas and subjected suddenly to a constant radiant heat flux are*

Differential equation: $$\rho c \frac{\partial T}{\partial \theta} = \frac{k}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial T}{\partial r} \right)$$

Initial condition: $$T = T_o \quad \text{at} \quad \theta = 0$$

Boundary condition 1: $$\alpha q = - k \left(\frac{\partial T}{\partial r} \right) + \frac{a \rho_d c_d}{3} \left(\frac{\partial T}{\partial \theta} \right) \text{at } r = a$$

Boundary condition 2: $$\frac{\partial T}{\partial r} = 0 \quad \text{at} \quad r = \ell$$

The expression given previously[8] and written

$$\frac{T-T_o}{\alpha q a/k} = \frac{1}{x} \left\{ \left(1 + \frac{3t}{L^3} + \frac{6A^2}{L^3} \right) \operatorname{erfc} \left(\frac{A}{\sqrt{t}} \right) - \frac{6A^2}{L^3 \sqrt{\pi}} \frac{e^{-A^2/t}}{(A/\sqrt{t})} - \frac{2e^{-t/\phi}}{\sqrt{\pi}} \int_{A/\sqrt{t}}^{\infty} e^{-y^2 + A^2/\phi y^2} \, dy \right\} , \quad L \gg 1$$

satisfies the differential equation and the initial condition exactly and approximates the boundary conditions.

Numerical calculations involving series approximations of the integral appearing in the approximate solution above have been carried out for

* See Appendix for nomenclature.

selected values of the variables partially covering the ranges to be investigated experimentally. The results of these calculations are summarized in Figures 1 through 6, which show the dimensionless quantity $T-T_o/\alpha qa/k$ as a function of the dimensionless variables t and x and the dimensionless parameters ϕ and L. These figures are valid for the particle temperature equal to or less than about one-half the source temperature.

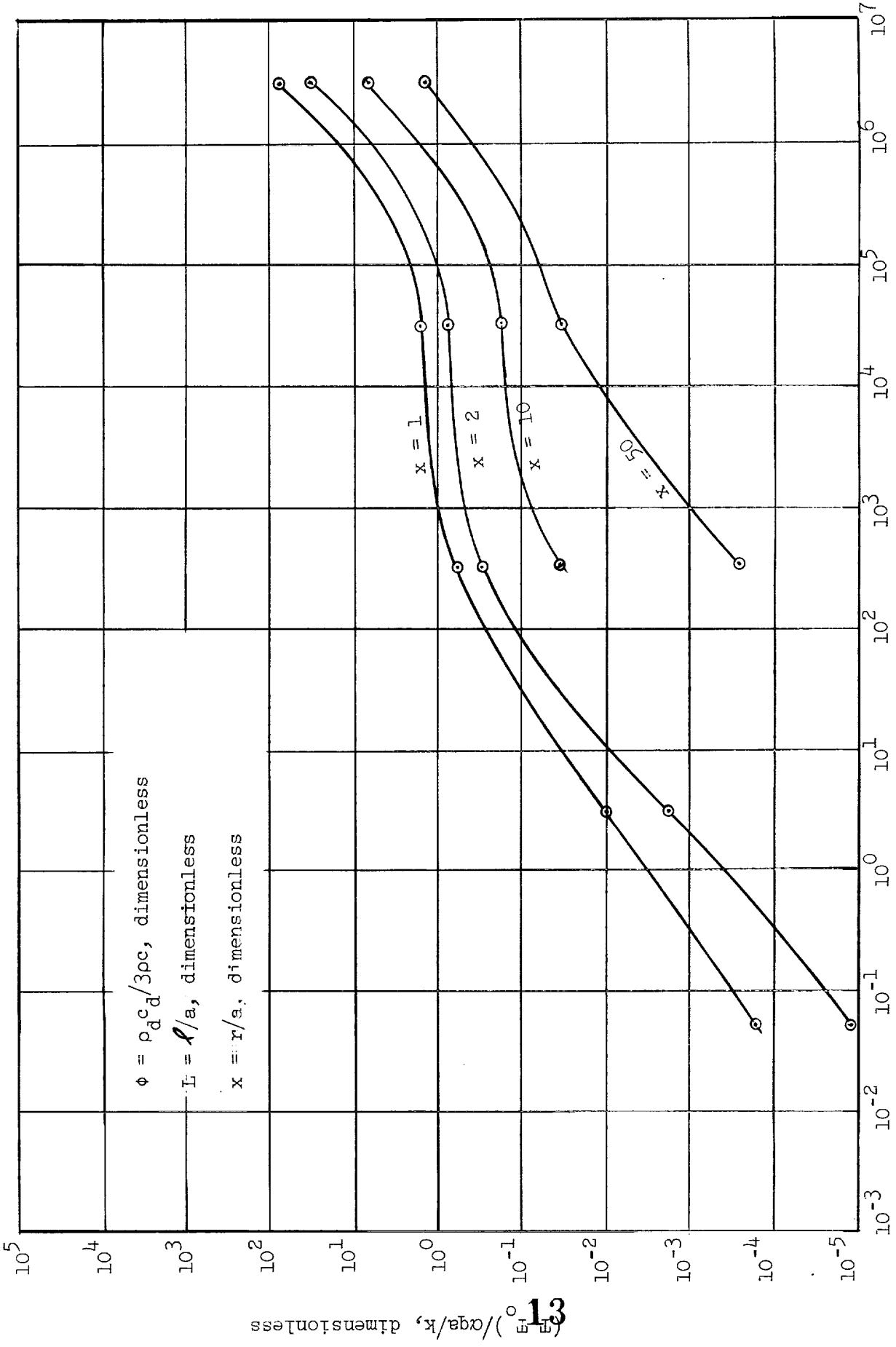
$\phi = \rho_d c_d / 3\rho c$, dimensionless
$L = \ell/a$, dimensionless
$x = r/a$, dimensionless
x = 1
x = 2
x = 10
x = 50
$t = k\theta/\rho c a^2$, dimensionless
$(E_{\lambda_b} - E_{\lambda_b})/\alpha q a/k$, dimensionless

Figure 1. Graphical Representation of Particle and Gas Temperatures in Dimensionless Quantities for $\phi = 300$ and $L = 50$.

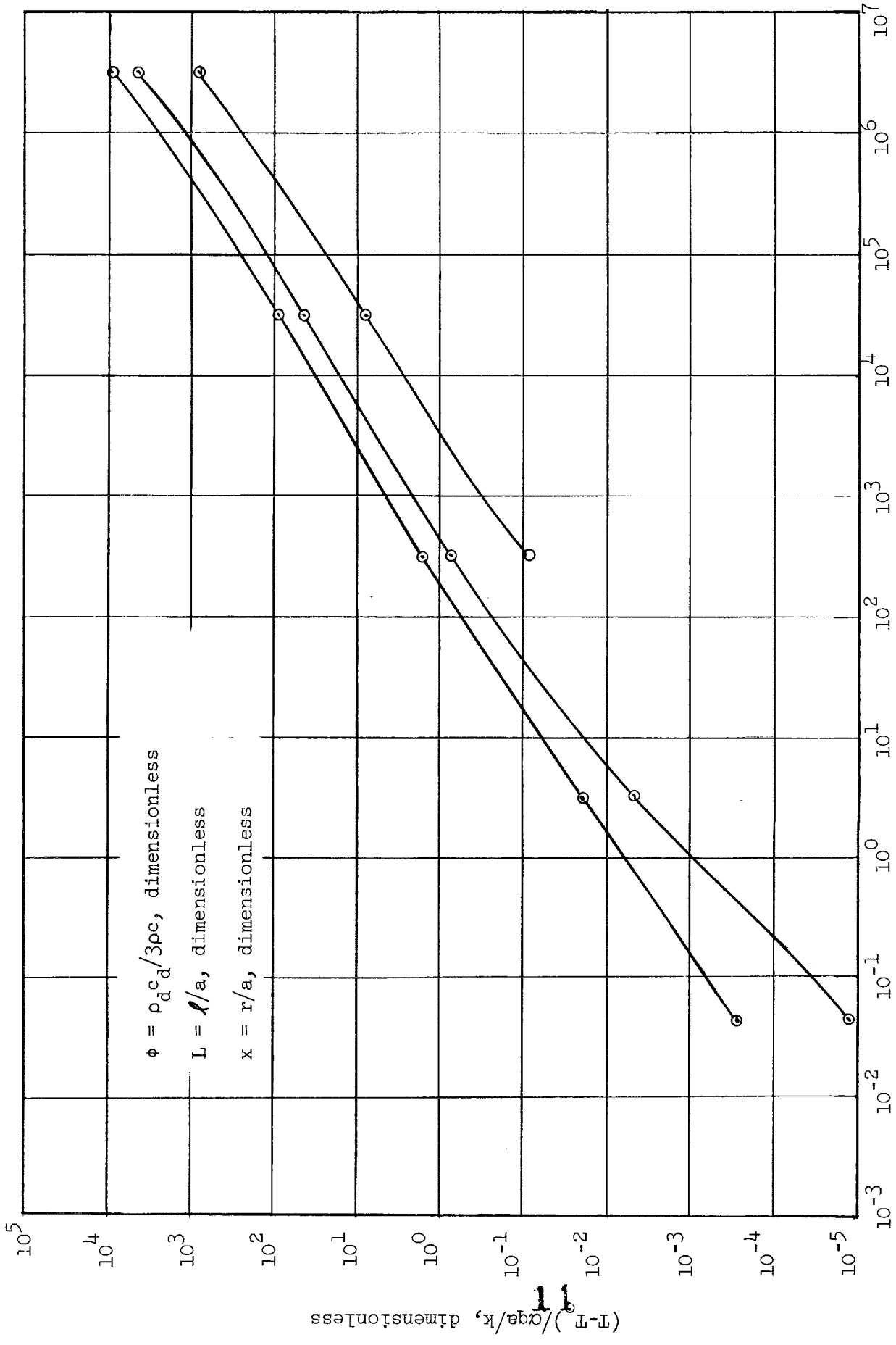
$\phi = \rho_d c_d / 3\rho c$, dimensionless
L = ℓ/a, dimensionless
x = r/a, dimensionless
$(T-T_\infty)/q_s a/k$, dimensionless
$t = k\theta/\rho c a^2$, dimensionless

Figure 2. Graphical Representation of Particle and Gas Temperatures in Dimensionless Quantities for $\phi = 300$ and $L = 10$.

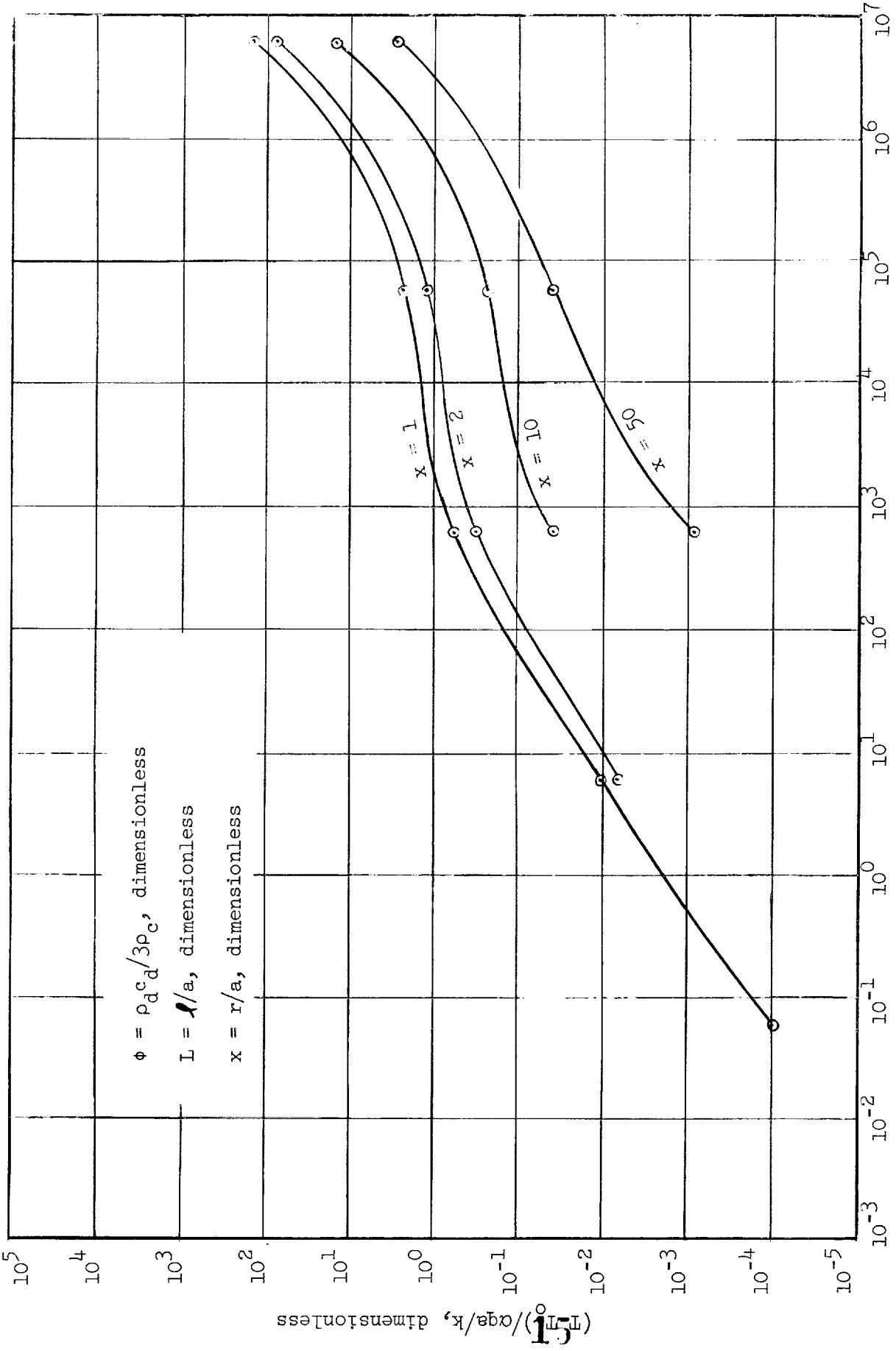
$(T-T_\infty)/\alpha qa/k$, dimensionless
$t = k\theta/\rho c a^2$, dimensionless
$\Phi = \rho_d c_d / 3\rho_c$, dimensionless
L = ℓ/a, dimensionless
x = r/a, dimensionless
x = 1
x = 2
x = 10
x = 50

Figure 3. Graphical Representation of Particle and Gas Temperatures in Dimensionless Quantities for $\Phi = 500$ and $L = 50$.

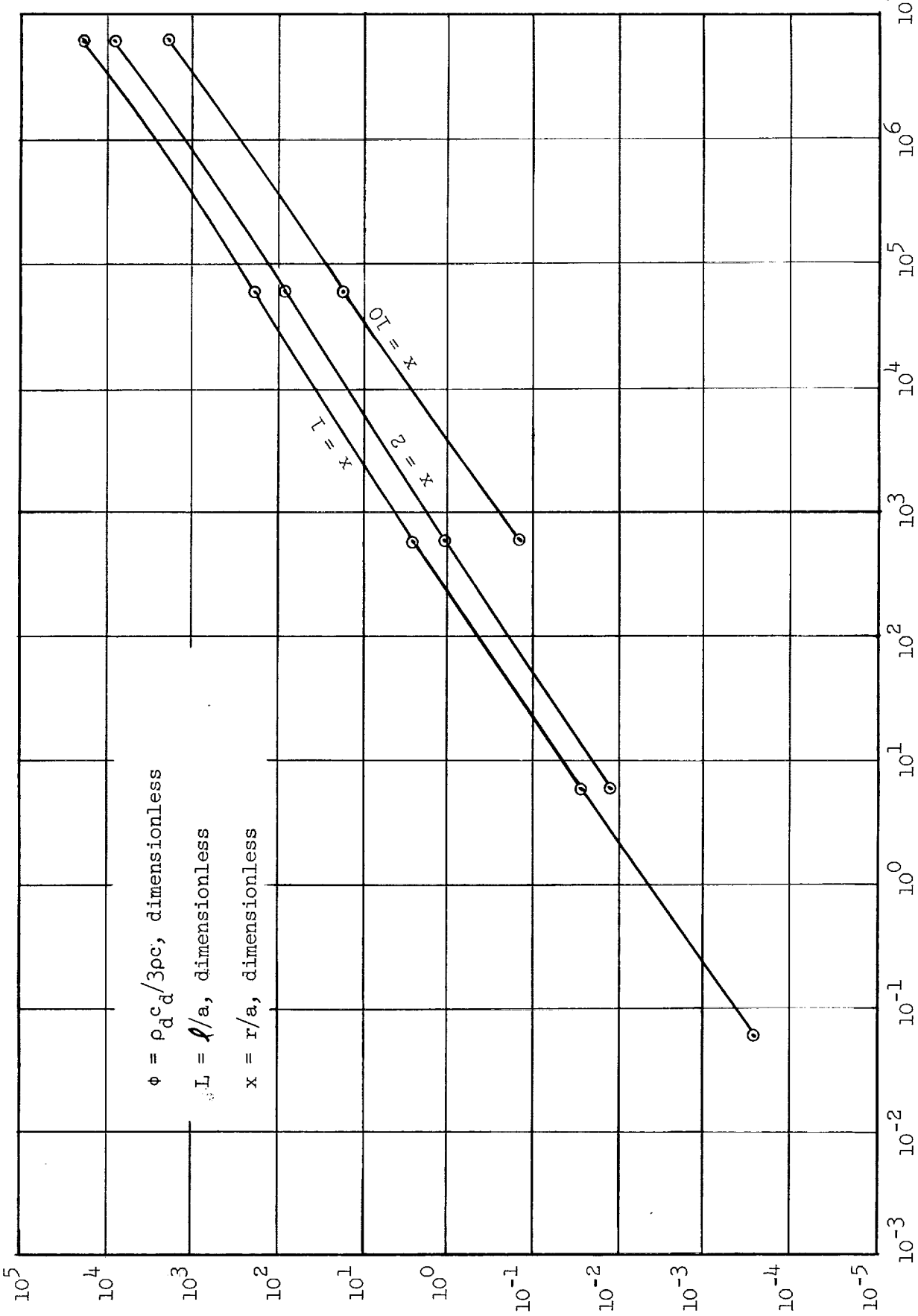
$\Phi = \rho_d c_d / 3\rho c$, dimensionless
$L = \ell/a$, dimensionless
$x = r/a$, dimensionless
$x = 1$
$x = 2$
$x = 10$
$t = k\theta/\rho c a^2$, dimensionless
$(T - T_o)/\alpha q a/k$, dimensionless

Figure 4. Graphical Representation of Particle and Gas Temperatures in Dimensionless Quantities for $\Phi = 600$ and $L = 10$.

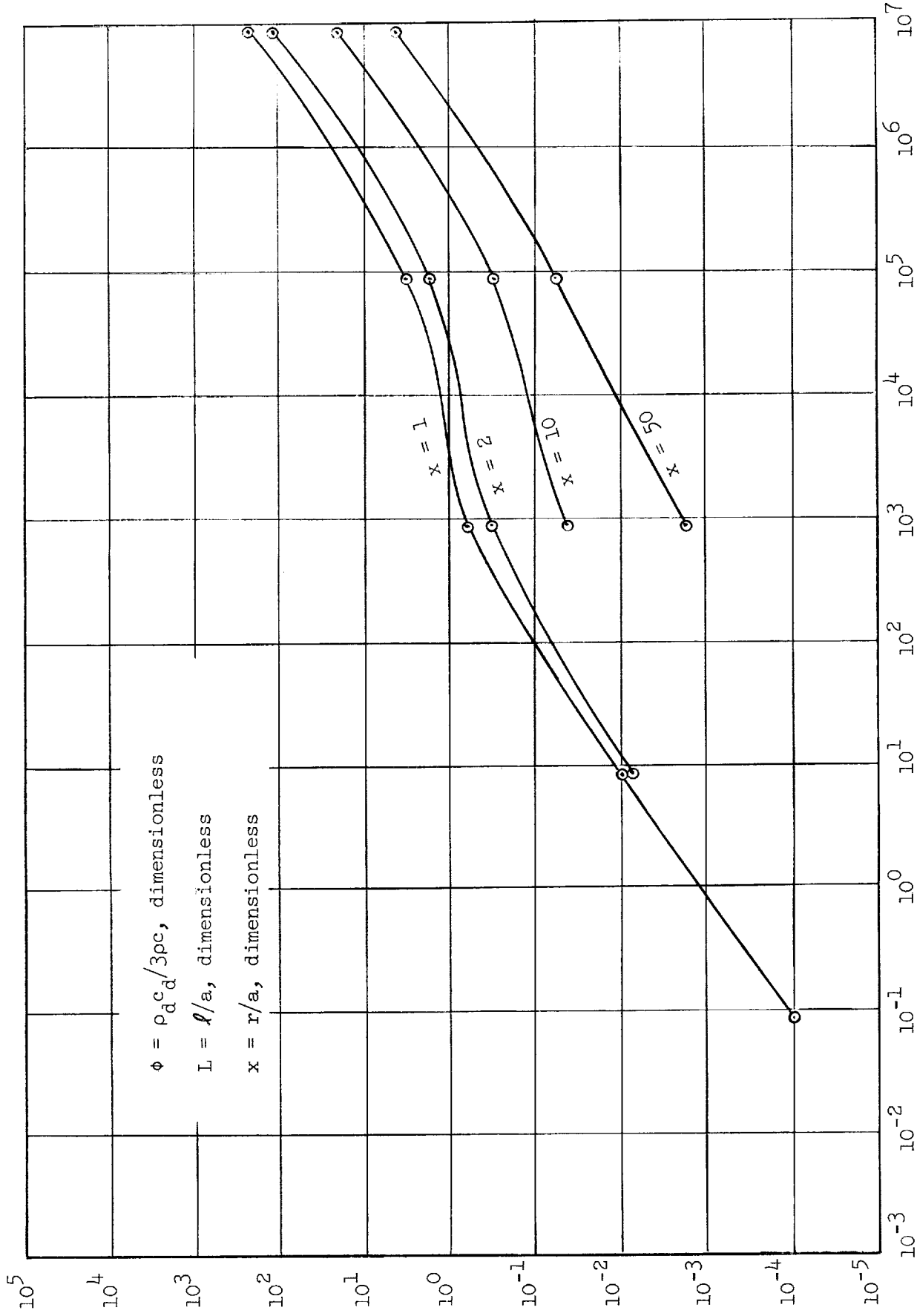
$\Phi = \rho_d c_d / 3\rho c$, dimensionless
L = ℓ/a, dimensionless
x = r/a, dimensionless
x = 1
x = 2
x = 10
x = 50
$(T-T_o)/\alpha q a/k$, dimensionless
$t = k\theta/\rho c a^2$, dimensionless

Figure 5. Graphical Representation of Particle and Gas Temperatures in Dimensionless Quantities for Φ = 900 and L = 50.

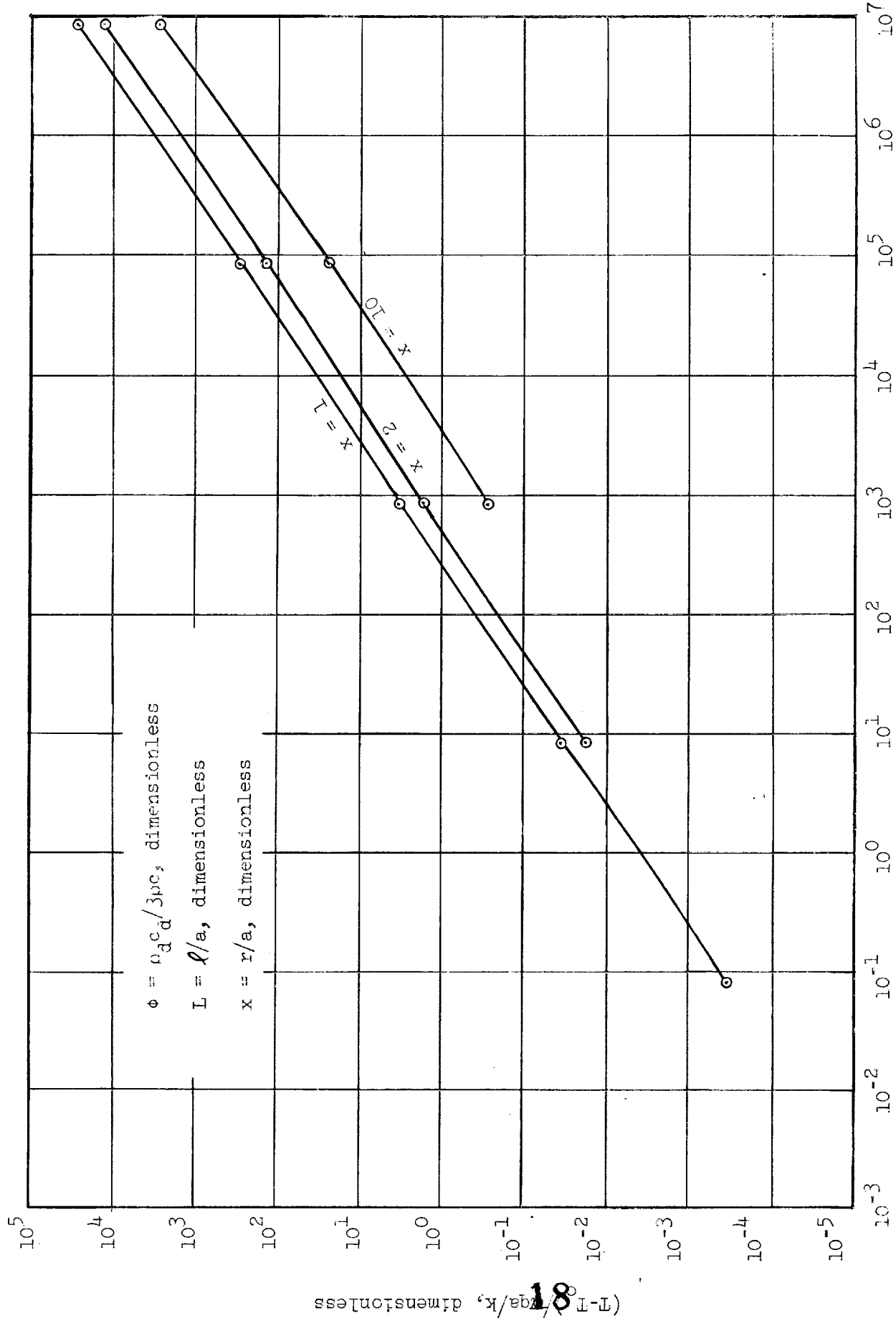
$\Phi = \omega_d c_d d/3\mu c_s$, dimensionless
L = ℓ/a, dimensionless
x = r/a, dimensionless
x = 1
x = 2
x = 10
$(T-T_\infty)/\gamma qa/k$, dimensionless
$t = k\theta/\rho c a^2$, dimensionless

Figure 6. Graphical Representation of Eqn. 14 and 15 Temperature Re-
[illegible] dimensionless parameters [illegible]

IV. EXPERIMENTAL DEVELOPMENT

A. Experimental Procedure

An apparatus with which to investigate experimentally both the absorptive properties of particulate matter and the particle-gas heat transfer interaction is just now being completed. The procedure on which its design is predicated will be (1) to expose an aerosol, well characterized as to particle shape, size, surface area, and concentration, to a radiant field in which convective and conductive heat effects are reduced to a minimum and, (2) to measure calorimetrically the energy absorbed and, if possible, the particle and gas temperatures. The first measurement is directly related to the absorptive power of the suspended solids and, hence, is a measure of that property. The determination of the particle and gas temperatures will afford an insight into the transfer of the heat absorbed by the particles to the surrounding gas.

The experiments are to be conducted on aerosols flowing in a quartz tube through a radiant field. The quartz conduit is protected from extraneous heat transfer effects other than radiation by enclosure in an evacuated air space the outer surface of which is air-cooled. The particle cloud is to be generated at a constant rate and pre-conditioned to a steady, known temperature. Then, after passing through the radiant field, the cloud will be cooled calorimetrically to determine the heat absorbed. A filter mechanism will remove the suspended particles from the air and return them to the aerosol generator for re-use.

A complete description of the apparatus and each of its components follows. Figure 7 is a photograph of the assembly.

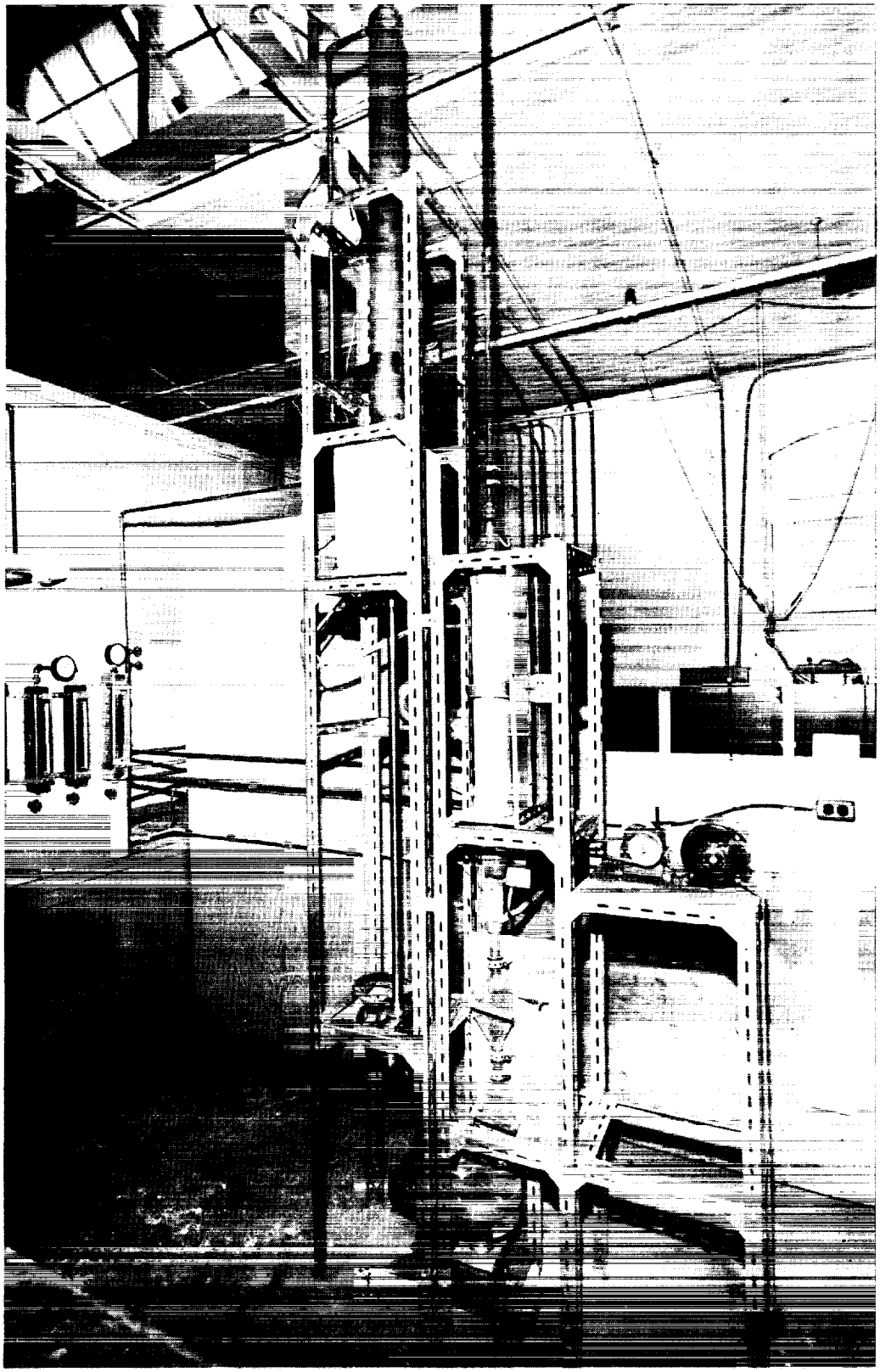

Figure 7. Photograph of Apparatus.

B. Description of Apparatus

1. Particle Cloud Preparation

The particle cloud generator pictured in Figure 7 and drawn in detail in Figure 8 produces the aerosol. As shown in section A-A of the drawing, a powder charged to the generator collects behind a retaining partition in the rotating container. The generation process requires a thin layer of powder, adhering to the felt covered bottom of the container, to feed continuously beneath the retaining partition. The layer thus formed is carried by the revolving surface under the atomizing nozzle pickups where the powder is entrained in air passing upward through them. There, deagglomeration results from the high shear forces generated by flow through the small diameter passages, across which the pressure drop is approximately 50 psig. After being atomized, the newly formed particle cloud passes through a length of pipe (L/D = 100) to allow the stream from the nozzle to mix thoroughly and to reach a steady state flow condition. The entrance length is enclosed in a constant temperature water jacket to bring the aerosol to a known temperature for use later in computing an overall heat balance on the suspension system.

Trial experiments were required to design a suitable deagglomeration nozzle to handle a large flow rate and still produce a uniformly dispersed cloud with steady flow characteristics. Originally, a venturi reducing the channel diameter to about 0.03 inch was employed to disperse the powder-air mixture issuing from the generator assembly. At that time the powder was made airborne by entrainment with the air as it passed through a perforated plate that covered the inlet to the aerosol conduit. In practically every case heavy agglomerates would form a fluidized bed in the pipe leading to the venturi. The venturi was then placed in the aerosol

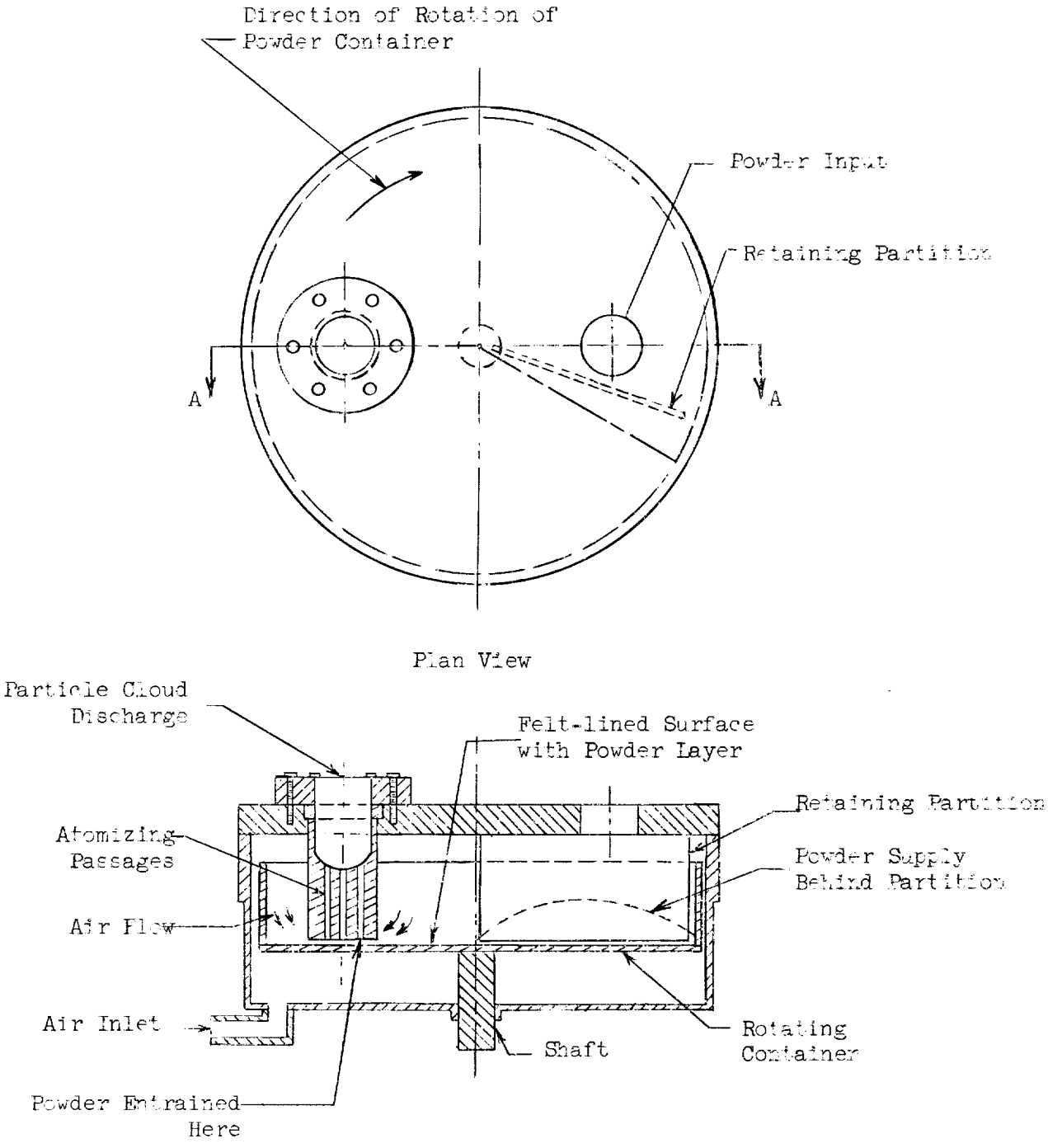

Figure 8. Particle Cloud Generator.

generator to avoid the fluidizing effects, but again the powder entrainment was unsteady. The most satisfactory arrangement was the employment of multiple, small diameter passages in the generator which served both as pickup tubes and as deagglomeration nozzles. Suspensions up to 0.05 per cent solids by volume and equal to 75 per cent by weight for dense materials have been produced.

The aerosol conduit is presently 0.5 inch in diameter to avoid overloading the compressed air system of the laboratory. Future experiments may require an independent air supply.

2. Radiant Heating Section

After preparation, the particle cloud is exposed to a radiant field produced by Kanthal wire, (Kanthal Company, Stamford, Connecticut) electric resistance heaters supported in grooves spiraling up the inner walls of a refractory enclosure constructed with Johns-Mansville 23 refractory brick. Two heaters are employed, one for the upper and the other for the lower half of the furnace. Each is composed of 30 feet of 0.333 ohm per foot wire wound into a 0.5 inch diameter coil. The windings are spaced closer at the ends of the furnace to compensate for the heat losses there and thus give a more uniform temperaure over the heated area. Further, temperatures of the two coils are controlled by independent means; this arrangement makes it possible to reduce the temperature differences resulting from convective currents within the furnace. A maximum of 4 kw can be supplied to the furnace and 2300° F is the maximum operating temperature for the resistance wire. Presently, the heated length of aerosol path is 12 inches. Figure 9 is a sectional drawing of the assembly.

The aerosol conduit passing through the radiant field is a 13 mm ID quartz tube with a 1.0 mm wall thickness. Surrounding this tube are two

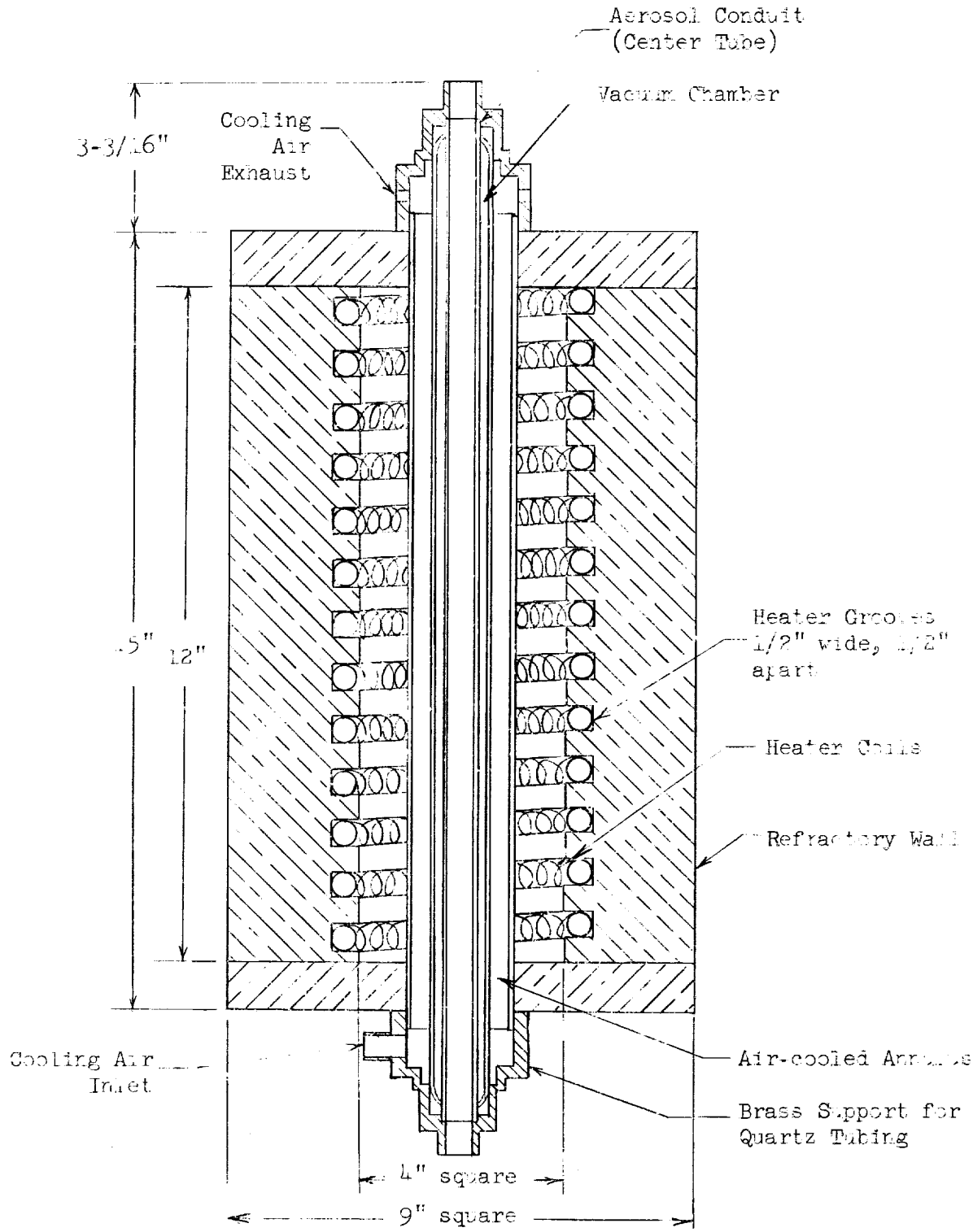

Figure 9. Radiant Heater

others, one 25 mm ID with a 1.0 mm wall thickness and the outermost one 54 mm ID with a 1.5 mm wall. The middle tube is sealed to the aerosol conduit and the annular enclosure thus formed is evacuated to a pressure of approximately 1.0 micron of mercury to reduce heat transfer across the enclosed space into the suspension. Air is circulated in the outer annulus to protect the outer quartz tubes from the high furnace temperatures. The air temperature in the outer tube can be kept below 200° F with air supplied from a suction fan. Because of the vaccum between this air stream enclosure and the aerosol conduit, very little heat can be transferred except by radiation to the aerosol system being studied. Further, since the heat transfer across the vacuum space is by conduction only, an accurate evaluation of its effect can be made. Some energy is absorbed by the quartz tube carrying the aerosol; this correction, too, is small and can be determined by experiment.

The transmission efficiency for a 2 millimeter thickness of the quartz employed here is given in Figure 10. Reflection losses are not included. The transmission between wave lengths of 0.3 micron and 3.5 microns is well over 90 per cent except for a small dip at 2.7 microns. Above 5 microns the transmission is nil. For a source temperature of 2300° F about 75 per cent of the radiant energy is thus transmitted.

It would be desirable to have either black body radiation from a constant temperature or a monochromatic source. True radiation properties with respect to either of these conditions would then be directly apparent from calorimetric determinations. The present furnace, however, does not have these properties. Measurements of particle radiation properties, therefore, are to be expressed as ratios referred to those of a large surface of the same material exposed to the same radiation field. Deviations of

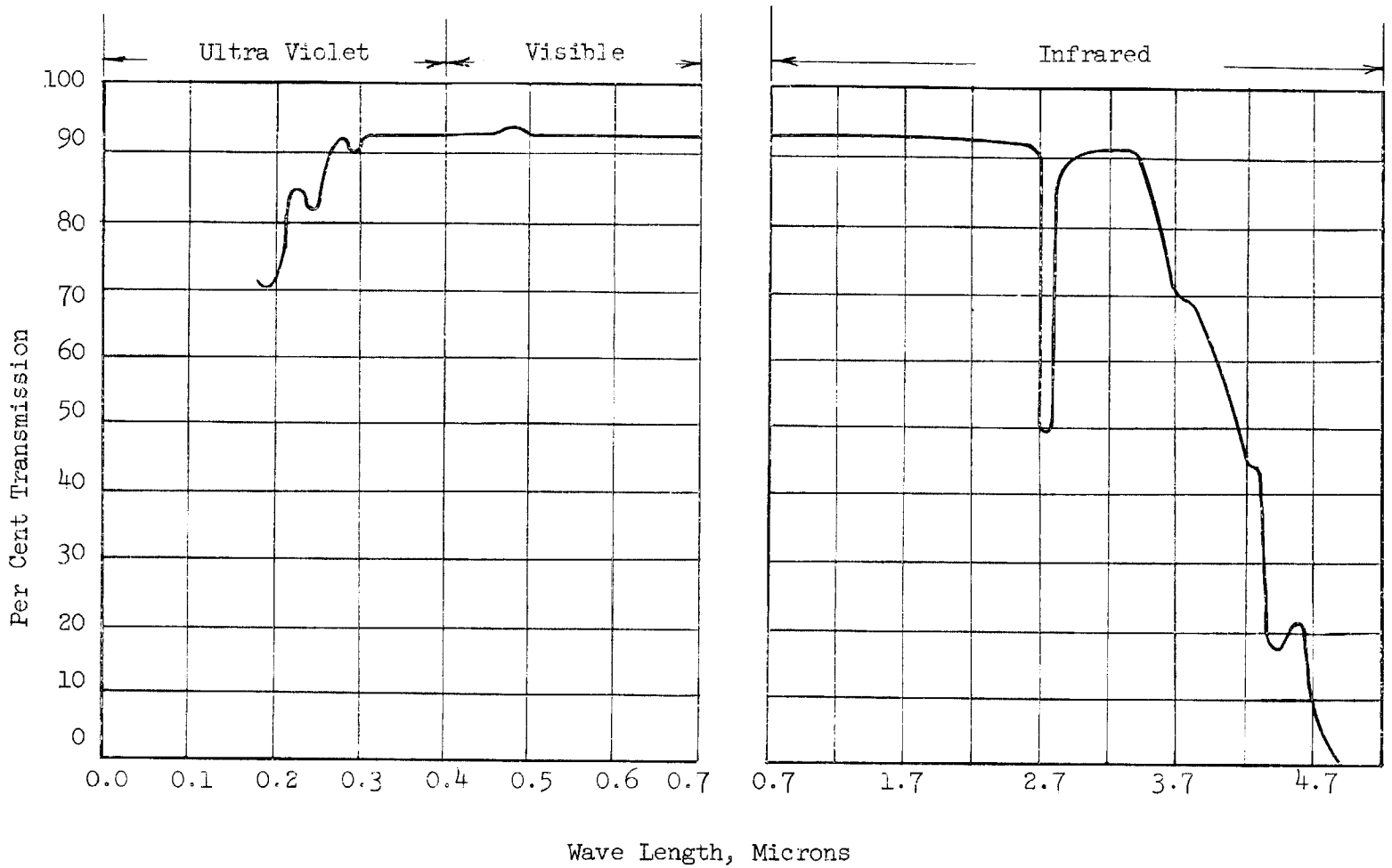

Figure 10. Transmission Characteristics of Quartz Tubing Used in Radiant Heaters.

radiation characteristics from this reference will be primarily due to the subdivision of the material into small particles. It is anticipated that particle radiation properties referred to black body or monochromatic radiation can be obtained from standard measurements on a large plane surface of the material involved and then be corrected by the results of this investigation. This approach is not exact but may be sufficient for initial study. It is recognized that radiation properties are functions of particle dimensions as compared with the wave length of the incoming radiation and that the results obtained in this work will be influenced by the radiation characteristics of the furnace walls. By varying the diameter of the particles employed, however, the effects of wave length changes may be studied.

3. Calorimeter

A concentric, single pass, tube-and-shell heat exchanger measures the heat that the suspension absorbs during its passage through the radiant field. The unit shown in Figure 11 is 4 feet long with a 0.5 inch ID conduit to carry the gas-particle suspension. This conduit is surrounded by a one inch tube containing a cooling medium flowing counter-current to the suspension. Either air or water can be used as the coolant, depending on the amount of heat flux being measured. Air, having the lower heat capacity will be used for the lower aerosol heat contents. A vacuum chamber surrounds the heat exchanger to insulate it from ambient room conditions. The outer wall of this chamber is also lined with aluminum foil to reduce radiation losses.

The overall heat leak with a pressure of one micron of mercury in the vacuum chamber is less than 0.5 Btu/hr by conduction and 0.03 Btu/hr

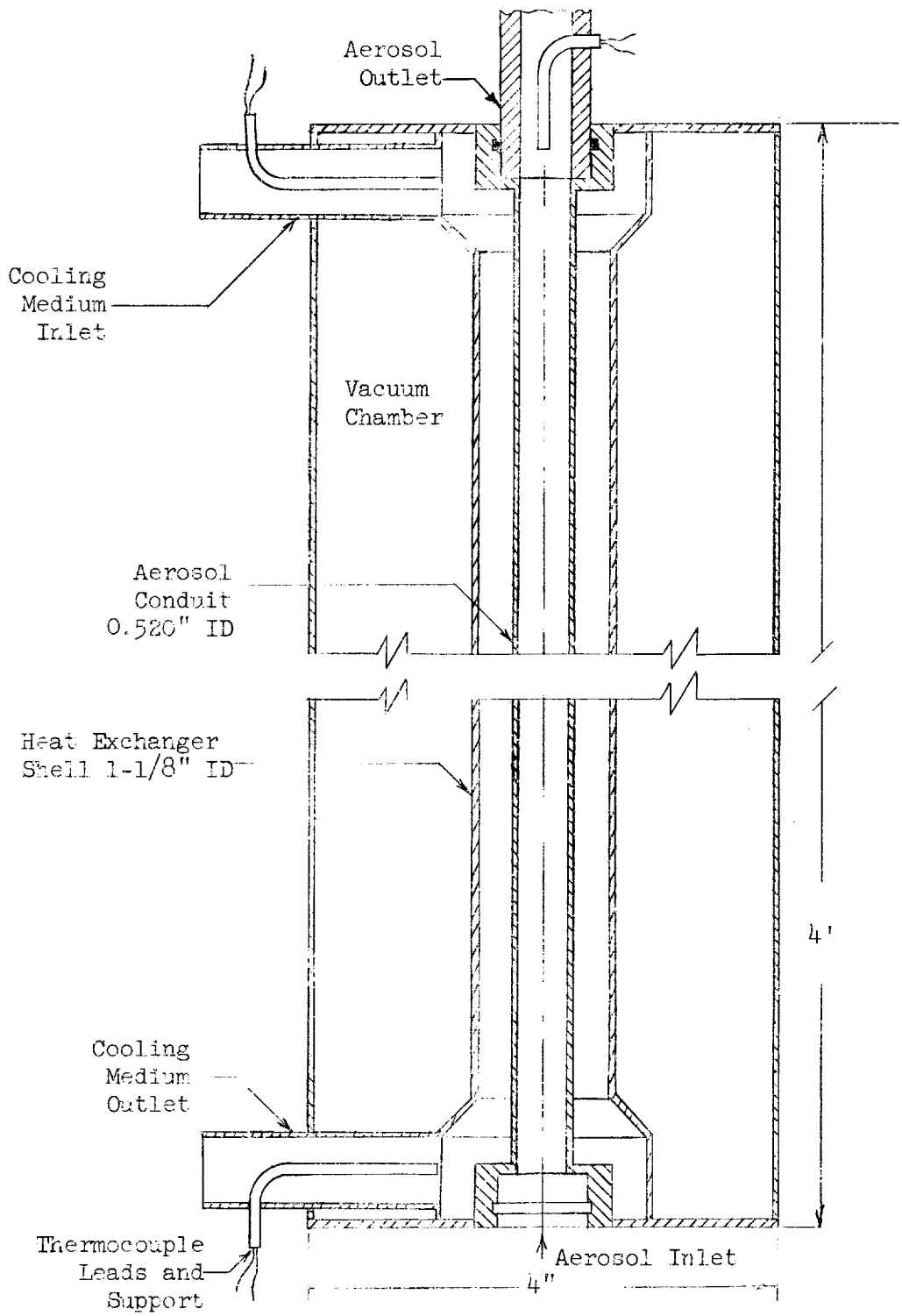

Figure 11. Calorimeter with Thermocouple Installations

by radiation for temperature differences up to 20° F across the vacuum. Some heat leak occurs at the base of the calorimeter. Circulating the effluent cooling medium through a protective coil embedded in a suitable insulation material, pulverized cork for instance, reduces this loss to a negligible value. It is estimated that heat absorption rates as low as 10 Btu/hr can be measured with acceptable accuracy.

Measurements of the cooling medium inlet and exit temperatures and the aerosol exit temperatures are to be made with copper-constantan thermocouples arranged as shown on the figure. These temperatures together with the mass flow rates of the two streams afford a heat balance for each and the evaluation of the heat content of the aerosol. The temperature of the aerosol as it leaves the furnace is not to be determined since it would be extremely inaccurate due to radiation there and to the uncertainty of the energy distribution between the solid and gas phases.

After calorimetric measurements of radiant energy absorption have been well established, efforts can then be made to study the distribution of heat between the particles and the air. It is anticipated that a high velocity, shielded thermocouple arranged to deflect all particles from the sensing element can be used to measure the gas temperature. The particle temperatures would then be calculated from heat balances on the total system and on each of the two phases. These measurements are expected to be difficult to accomplish, but from the theoretical calculations the technique seems feasible. In the radiant heating section, the ratio of energy retained by the particles to that received by the gas is approximately $2\phi/L^2$, where $\phi = \frac{\rho_d c_d}{3\rho c}$ and $L = \ell/a$. For a 0.05 volume per cent concentration of zinc particles in air this ratio is 9.5. Thus,

about 90 per cent of the heat is estimated to be in the particles. From an overall heat balance determination and a knowledge of the gas temperature it should be possible to check these calculations experimentally.

Pyrometric determinations of particle temperatures would be desirable. This method unfortunately is not applicable at the temperatures involved here and the combined target area of the suspended particles is unfavorably small. This technique could possibly be used should a higher temperature furnace be built later.

4. Particle Concentration Monitoring

Upon leaving the calorimeter the particle cloud passes through the return bend at the top of the apparatus and in the downward path is monitored for consistency in concentration by measuring the transmission of light through it. The device presently being constructed for this purpose is shown schematically in Figure 12. The electronic circuit indicated in the figure provides a constant voltage for the lamp which thus generates a light beam of substantially constant intensity. The lamp is positioned so that it illuminates a photoelectric cell diametrically across the aerosol path. Since the light transmitted across this space is a function of the particle concentration, the photocell current is a direct measure of the number of particles present. By recording this current during an experiment it will be possible to evaluate the constancy of the particle cloud concentration. Further, by knowing the continuous variations of particle concentration with time, the total amount of powder passing through the system in a given time interval can be accurately calculated by graphical integration.

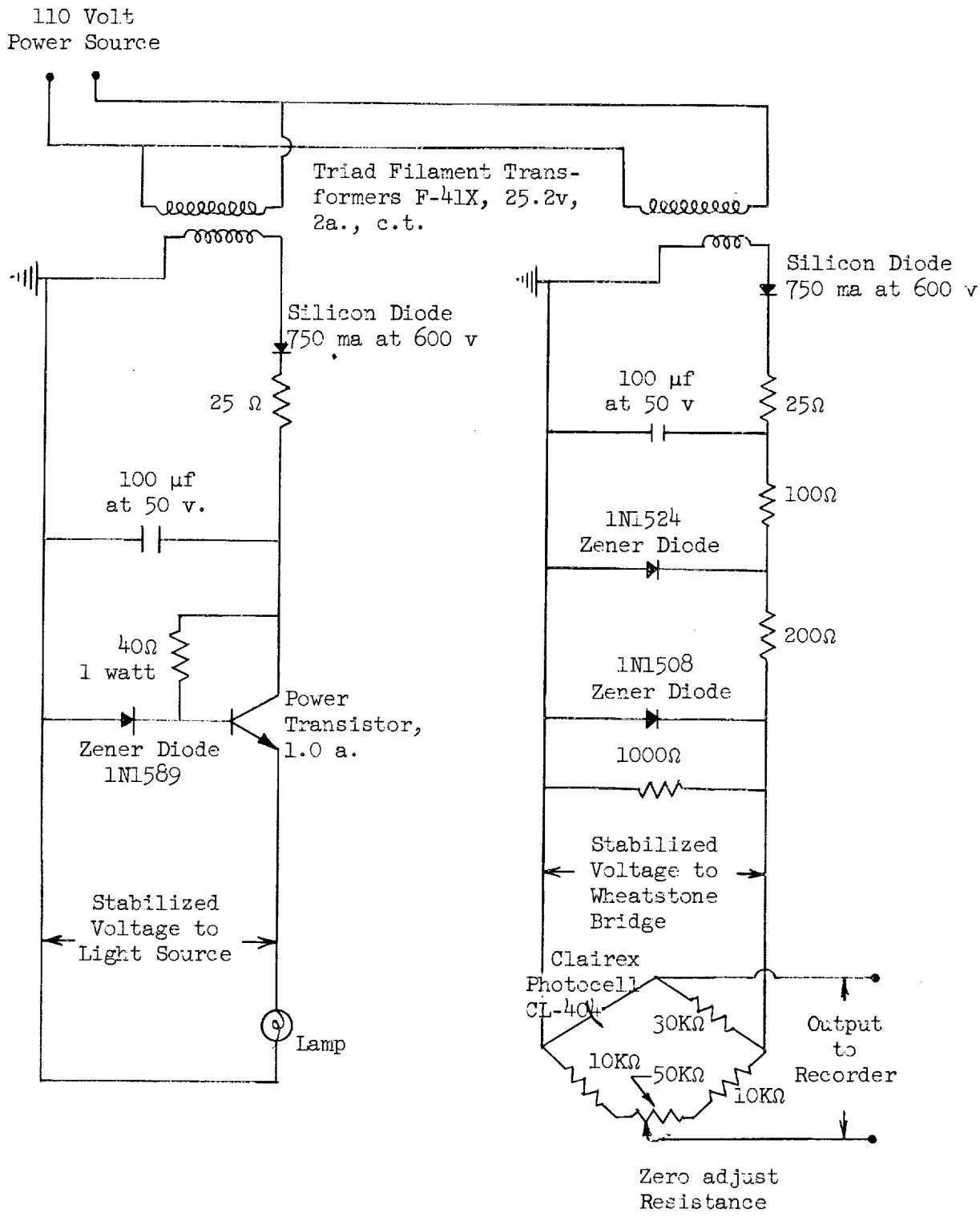

Figure 12. Schematic Diagram of Electronic Particle Concentration Monitor.

Light transmission measurements are intended to serve primarily as a means of monitoring the fluctuations in particle concentration during the course of experiments. The actual particle concentrations are to be determined for each experiment by direct sampling. It is possible, of course, to calibrate the electronic instrument for each powder to be investigated and to convert the transmissivities directly into concentration. Considerable uncertainty, however, might arise with this approach due to changes within the instrument. For instance, the illumination would vary with the cleanness of the conduit walls and changes in the illumination power of the lamp and within the electronic components themselves. To get maximum precision, therefore, it is much more expedient to make a partial calibration for each experiment for the conditions prevailing at that time.

A probe inserted into the aerosol conduit will be employed to sample the aerosol stream. A small air pump with an appropriate control valve removes a portion of the aerosol flow and a staplex type cellulose filter (TFA Type "S", The Staplex Company, 777 Fifth Avenue, Brooklyn 32, New York) collects the entrained solids. Air flow rates in the aerosol conduit and in the sample probe are to be measured with rotameters so that the isokinetic sampling can be established and the volume of aerosol removed can be calculated. The amount of solid material will be determined gravimetrically. The sampling unit remains to be constructed.

A 2 foot length of glass tubing, shown in Figure 7, forms part of the aerosol circuit to provide for visual inspection of the particle cloud. Although not required, direct observation makes the system much easier to operate.

5. Powder Collection and Return Mechanism

Finally the aerosol enters the bag filter (shown in Figure 1) where the powder is separated from the air stream. The bag filter is 4 inches in diameter and has 22 inches of useful length. The filter itself is traversed by a circumferential air jet which dislodges the filtered material and provides continuous operation of the filter. The traversing action is obtained with a guide that follows a right-hand helical groove along a cylinder in one direction and, at the end, reverses to follow a left-hand helix to the opposite end. The shifting of the guide from one helix to the other is accomplished by a smoothly connecting groove at each end of the cylinder. The guide has sufficient length to avoid changing helixes where they cross. The mechanism is driven by the motor and gear reducing unit.

Two discharge valves below the filter transfer the collected powder back to the aerosol generator for re-use. These valves, shown in Figure 13, are arranged in series and are operated so that one valve is always closed to prevent compressed air from escaping from the aerosol generator. Previous plans were to make the valve automatically activated. It has been found, however, that manual operation is more feasible at the moment.

C. Controls and Instrumentation

A variety of control and measurement devices are required for the operation of the apparatus. Figure 14 is a photograph of these instruments. The right side of the panel, as shown, contains the necessary rotameters for measuring the various air and water flow rates required. The rotameters at the extreme right measure the air flow rate supplied to the calorimeter

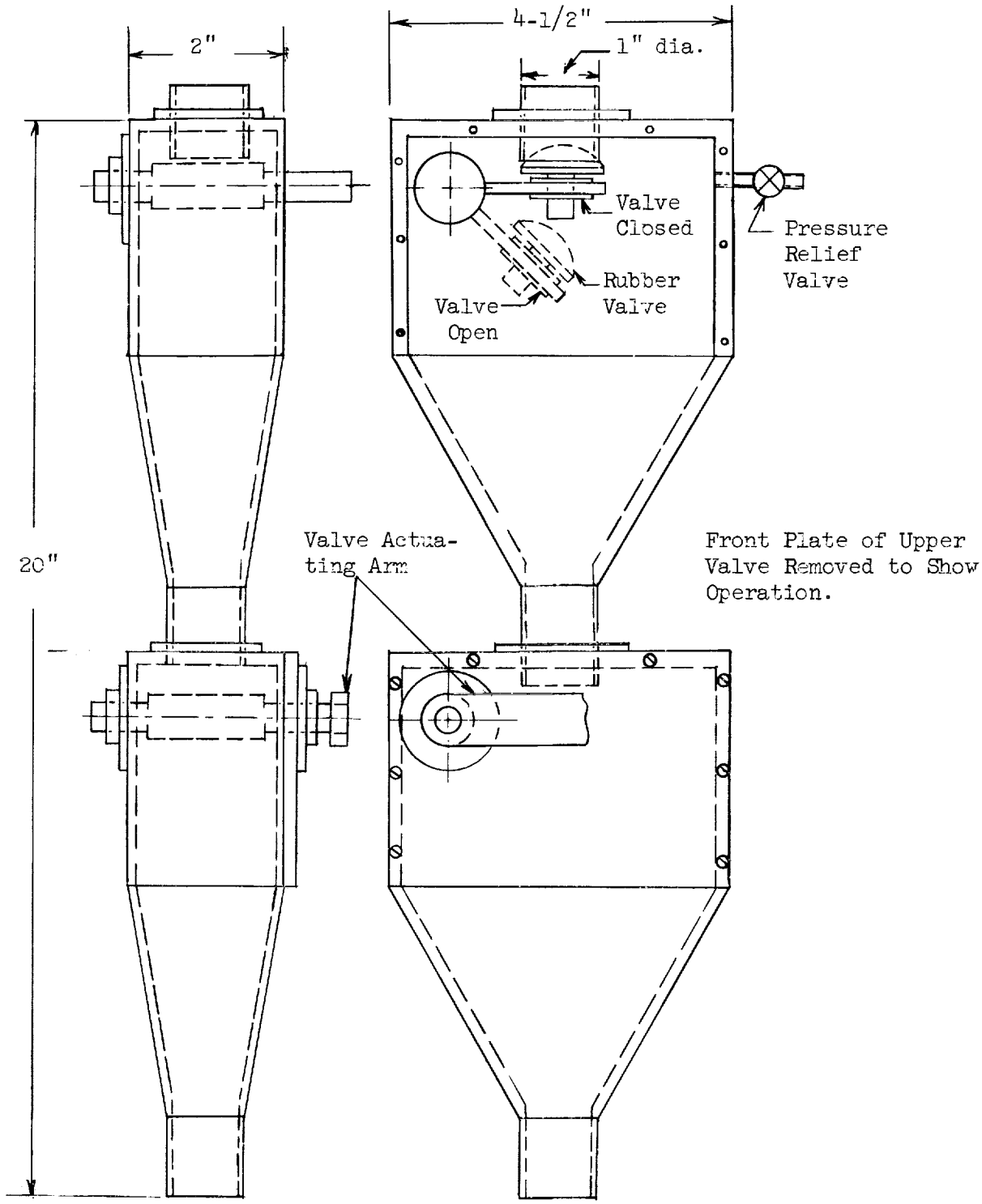

Figure 13. Powder Discharge Mechanism.

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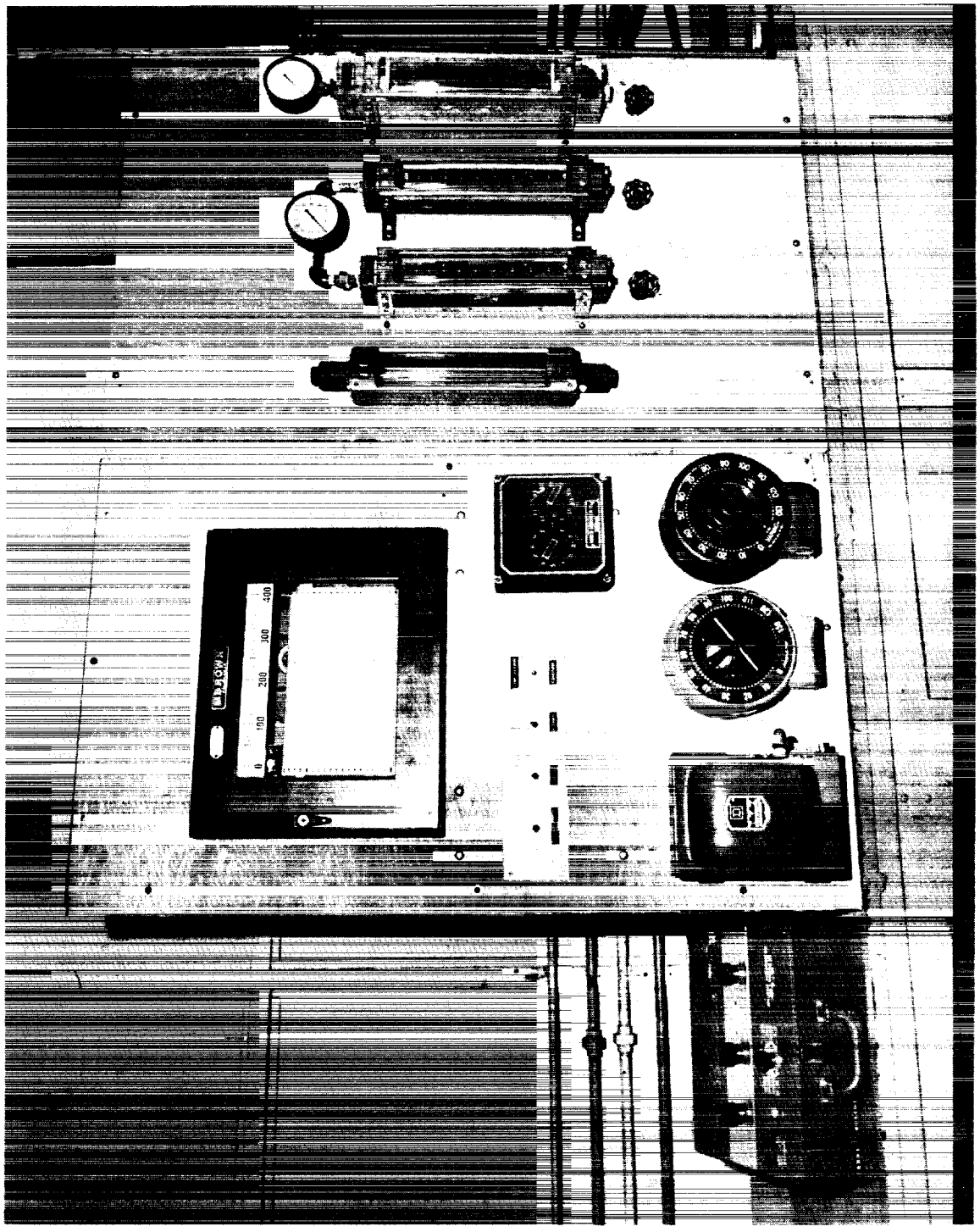

Figure 14. Photograph of Instrument and Control Panel.

for cooling the particle cloud. The intermediate rotameters meter air to the particle cloud generator for producing the aerosol. The remaining rotometer is to meter water to the calorimeter when water is used as the cooling medium. The valves beneath each rotameter control the flow through the meter above.

The left part of the panel contains the power and electronic equipment. Across the lower portion are the master switch for the apparatus and the two variable auto-transformers that supply power to the furnace coils. Above is the switch panel for the various power sources used throughout the apparatus, and at the right-center is the switch box for the temperature measurement system. The recorder is to monitor the particle cloud concentration, and the potentiometer is to be used for temperature measurement.

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V. FUTURE WORK

The results of the numerical calculations will be analyzed in detail to see what effects are important and what effects may be neglected with the objective of developing a practical mathematical treatment. An attempt will be made to account for turbulent mixing effects and for nonuniformity of particle concentration, velocity and temperature distributions, and radiant energy flux. Analyses of experimental data which will soon be available will guide this development. The analytical procedure mentioned previously[8] of dividing the heat transfer section into an arbitrary but finite number of zones and making energy balances on each of these zones will then be started.

Future experimental work will consist of the calibration of the various measurement systems of the apparatus and the subsequent collection of experimental data. It is anticipated that sufficient data will be collected in the near future for a significant evaluation of particulate radiation properties and for guiding the study of the overall heat transfer process. Additional measurements will be needed to determine the average temperatures of the solid and gas phases for investigating the particle-gas heat transfer interactions. The latter experiments will require the construction of a shielded thermocouple for measuring air temperatures. The general nature of such a device is well known but the exact design remains to be determined.

Respectfully submitted,

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Project Director

Approved:

for Wyatt C. Whitley

Frederick Bellinger, Chief
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VII. APPENDIX. DEFINITION OF SYMBOLS

Roman Symbols

A = $(x-1)/2$, dimensionless

a = particle radius, ft

c = gas heat capacity, Btu/lb$^{\circ}$F

c_d = particle heat capacity, Btu/lb$^{\circ}$F

k = gas thermal conductivity, Btu/hr-ft-$^{\circ}$F

L = ℓ/a, dimensionless

ℓ = $(3/4\ \pi n)^{1/3}$ = 1/2 mean distance between particle centers, ft

n = particle concentration, number/ft^3

q = radiant heat flux, Btu/hr ft^2

r = radius from particle center, ft

T = temperature, $^{\circ}$F

T_o = initial particle and gas temperature, $^{\circ}$F

t = $k\theta/\rho c a^2$

x = r/a, dimensionless

Greek Symbols

α = particle absorptivity, dimensionless

θ = time, hr

ρ = gas density, lb/ft^3

ρ_d = particle density, lb/ft^3

ϕ = $\rho_d c_d/3\rho c$, dimensionless